

Rare βp decays in light nuclei

MJG Borge¹, LM Fraile², HOU Fynbo³, B Jonson⁴, OS Kirsebom³, T Nilsson⁴, G Nyman⁴, G Possnert⁵, K Riisager³ and O Tengblad¹

¹ Instituto de Estructura de la Materia, CSIC, Serrano 113 bis, E-28006 Madrid, Spain

² Grupo de Física Nuclear, Universidad Complutense, CEI Moncloa, E-28040 Madrid, Spain

³ Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

E-mail: kvr@phys.au.dk

⁴ Fundamental Fysik, Chalmers Tekniska Högskola, S-41296 Göteborg, Sweden

⁵ Department of Physics and Astronomy, Ion Physics, Uppsala University, S-75120, Sweden

Abstract. Beta-delayed proton emission may occur at very low rates in the decays of the light nuclei ^{11}Be and ^8B . This paper explores the potential physical significance of such decays, estimates their rates and reports on first attempts to detect them: an experiment at ISOLDE/CERN gives a branching ratio for ^{11}Be of $(2.5 \pm 2.5) \cdot 10^{-6}$ and an experiment at JYFL a 95% confidence upper limit of $2.6 \cdot 10^{-5}$ for ^8B .

PACS numbers: 23.40.Hc, 27.20.+n, 21.10.Gv

Submitted to: *J. Phys. G: Nucl. Part. Phys.*

1. Introduction

The lightest chemical element in which beta-delayed proton (βp) emission has been observed so far is carbon, in the decay of ^9C . This paper explores the possibility of seeing the decay mode also in beryllium and boron, more specifically in the decays of ^{11}Be and ^8B . These nuclei are the lightest (not counting the deuteron) one-neutron and one-proton halo nuclei, respectively, and the possible βp decays are intimately connected to this structure. There are two reasons for this connection, the first being the factorization of the wavefunction into a halo and a core part that suggests “independent decays” of the two parts [1] which naturally leads to final states with a continuum proton; we shall discuss this model in the next section. The second connection is specific for β^- decays where one can derive the general expression [2]

$$Q_{\beta p}(^AZ) = (m_n - m_H)c^2 - S_n(^AZ) = 782 \text{ keV} - S_n(^AZ) \quad (1)$$

from which it is seen that the βp decay only occurs for nuclei with very low neutron separation energy. Similar relations exist for beta-delayed deuteron and triton emission that are known to take place close to the neutron dripline [1, 3]. So far βp decays

have only been observed following β^+ or EC decays. General recent reviews of these processes can be found in [3, 4].

The following section discusses the characteristics of the proposed decays in more detail including the estimated order of magnitude of the decay rate. The expected branching ratios are quite low and some general considerations are made on how they could be measured. Sections 3 and 4 give details on first measurements of the decays in ^{11}Be and ^8B from which upper limits on the branching ratios can be given. The final section gives our conclusions and the prospects of identifying the two decays.

2. Expected rates

A crucial feature of halo states is their intrinsic clustering so that (a major part of) the wavefunction will factorize into a halo part and a core part [5, 6]. Formally, the beta-decay can then be thought of in terms of separate decays of the core (c) and halo (h) parts [1]

$$\mathcal{O}_\beta(|c\rangle|h\rangle) = (\mathcal{O}_\beta|c\rangle)|h\rangle + |c\rangle(\mathcal{O}_\beta|h\rangle) \quad (2)$$

but the actual final states will of course in general be superpositions of the two terms on the right side e.g. to ensure they have proper isospin. If the states on the right hand side are close to being eigenstates for the final system one would expect a large resemblance between the decays of the core nucleus and the halo nucleus. Experimental confirmation of this idea may be found in the decays of ^{12}Be and ^{14}Be , which are quite analogous [7].

2.1. $^{11}\text{Be}(\beta p)$

The most recent mass tables [8] give $Q_\beta = 11509.2 \pm 0.5$ keV for the decay of ^{11}Be , which leaves 281 keV as the energy window for beta-delayed proton emission. Different assumptions on the decay mechanism can give widely different rates [9]. We shall therefore present several simplified models that lead to rather straightforward expressions for the decay rate, and start by considering sequential decays as described in R-matrix theory that can handle broad intermediate states. However, the classical R-matrix expressions may not give a sufficiently accurate description of the decay mechanism. At the other extreme are models that consider decays to proceed directly to continuum states, as has been assumed for most calculations of the related βd decays [1, 3].

Allowed beta decay of ^{11}Be will populate $1/2^+$ and $3/2^+$ levels in ^{11}B , but since these would decay to $^{10}\text{Be}+p$ with s-wave and d-wave protons, respectively, only the $1/2^+$ states can be expected to give a sizeable contribution. Out of the known states [10, 11] in the excitation energy range 10.0–12.5 MeV the only one that may have spin and parity $1/2^+$ is a state at 11.444 MeV with width 103 keV that has been seen to decay by emission of α particles, but where the spin is so far undetermined. The R-matrix expressions for β -decay have been derived for several cases, see [12] and references therein, but we shall here only consider a crude approximation based on the single-channel single-level case in which the energy spectrum is:

$$\frac{w_p}{w_{tot}} = T_{1/2} \frac{g_A^2}{K} f_\beta (Q - E) B_{GT} \frac{\Gamma/(2\pi)}{(E - E_0)^2 + \Gamma^2/4} \frac{P(E - E_t)}{P(E_0 - E_t)}, \quad (3)$$

where w denote the decay rates for the proton branch and the total beta decay, $T_{1/2}$ the experimental halflife, g_A and K the standard weak decay constants [3, 4], f_β the beta

decay phase space factor, B_{GT} the reduced Gamow-Teller matrix element squared, E_0 and Γ the level energy and width, and $P(E - E_t)$ the proton penetrability (E_t being the proton threshold energy). Several energy dependent terms in the denominator are here approximated as constants. To take into account that the level can decay both by emission of α particles and protons one should multiply by Γ_p/Γ_{tot} to get the intensity of the proton spectrum. This ratio is unknown, but may in the best case (if the proton width is close to a single-particle width) reach 1/2. The GT strength B_{GT} can at most be 3 (the value for a pure neutron to proton decay). Inserting these maximum values the total branching ratio becomes $1.0 \cdot 10^{-6}$, but a realistic value could be lower by an order of magnitude or more. The predicted spectrum is given in figure 1 for the case where the intensity (the product $B_{GT}\Gamma_p/\Gamma_{tot}$) is a factor 50 below the maximum, i.e. where the branching ratio is $2.0 \cdot 10^{-8}$.

As an intermediate step we consider next the suggested modification of the R-matrix formalism containing the opposite time ordering [13], i.e. where the neutron is emitted before beta decaying into a proton. As argued by Barker [14], who presents a more detailed derivation analogous to the way photon emission is treated, this may be a simple way to effectively include the decays to continuum states into the R-matrix framework. In the limit where only the “emission before decay” process is included the decay rate becomes

$$\frac{w_p}{w_{tot}} = T_{1/2} \frac{g_A^2}{K} f_\beta(Q - E) B_{GT} \frac{1}{\pi} \frac{P(E - E_t) \gamma^2}{(S_n + E)^2}, \quad (4)$$

where S_n is the neutron separation energy in ^{11}Be and the parameter γ^2 quantifies the neutron emission probability. For a decaying level it is related to the level width through $\Gamma = 2P\gamma^2$ and it must be less than the single particle width (the Wigner limit, here 5.8 MeV). The total branching ratio is proportional to γ^2 and is at most $2.5 \cdot 10^{-8}$. The predicted energy distribution is also plotted in figure 1.

Finally, the simple model for decays directly to continuum states [15] gives

$$\frac{w_p}{w_{tot}} = T_{1/2} \frac{g_A^2}{K} f_\beta(Q - E) B_{GT}(E) \frac{P(E - E_t)}{R} \frac{mc^2}{2\pi^2(\hbar c)^2}, \quad (5)$$

where m is the reduced mass of the outgoing proton and R is the channel radius used to evaluate the penetrability. The Gamow-Teller strength is now explicitly energy dependent since the final state wavefunction is a continuum state. The expression above results if one uses a plane wave approximation for the final state when calculating $B_{GT}(E)$. If one instead uses a Coulomb wave the effect of the transmission through the Coulomb potential is included in $B_{GT}(E)$ and one must replace the ratio P/R by the wavenumber k . The total branching ratio is in this latter case $2.3 \cdot 10^{-8}$, the corresponding energy distribution is given in figure 1. More realistic calculations will use distorted waves so that the final state strong interactions are also included. A recent more sophisticated calculation [16] in a two-body potential model gives a broad energy spectrum peaking at 0.1–0.2 MeV and a branching ratio of $3.0 \cdot 10^{-8}$. (This specific calculation includes both Fermi and Gamow-Teller contributions to the decay rate.)

To summarize, the different models predict somewhat different shapes of the energy distribution and give a branching ratio that typically is a few times 10^{-8} , but could range up to 10^{-6} . To see the decay mode an experiment therefore needs to be sensitive down to the 10^{-8} level, while considerably more intensity will be needed to separate the different models.

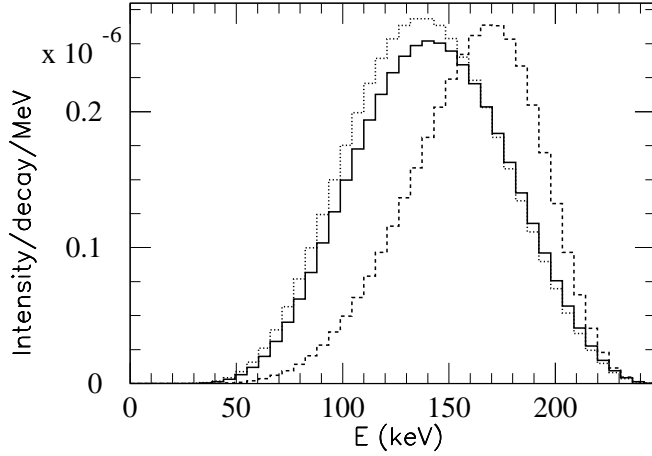


Figure 1. Energy spectra of beta-delayed protons from the decay of ^{11}Be predicted in three different models presented in the text. Sequential decay through the 11.444 MeV state in ^{11}B (dashed line), emission before decay (dotted line), decay to continuum (full line).

2.2. $^8\text{B}(\beta p)$

Turning now to ^8B two facts make the decay directly to continuum states less likely here: the smaller spatial extent of the halo in this nucleus and the fact that there is an excited state in ^8Be within the β -decay window (actually the EC-decay window) that the decay may pass through, namely the $1^+ T = 1$ state at 17.640 keV. It is situated 385 keV above the proton threshold and is known to decay mainly by proton emission [17]. If equation (2) is appropriate, we can estimate the matrix element of the transition to be the same as for the ground state decay of ^7Be into the ground state of ^7Li (the larger amplitude of the wavefunction in ^8B increases the rate by a factor 2.1 [18] but this is compensated by a factor 1/2 from the isospin Clebsch-Gordan coefficient squared). Both transitions are electron capture decays for which the phase space goes as the Q-value squared, so by scaling the half-life of ^7Be we obtain an estimate of the branching ratio of the βp transition of $2.3 \cdot 10^{-8}$.

Direct support for this estimate can be found from the three-cluster calculations in [19] that predict a B_{GT} to the 17.64 MeV state of 1.366 and 1.997 for two different potentials employed. This is in the same range as the B_{GT} of 1.83 for the ^7Be ground state transition.

Table 1. Q-values and separation energies in ^{11}Be beta-delayed particle decays.

x	p	n	α	t
$S_x(^{11}\text{B})$ (keV) ^a	11228.5 ± 0.4	11454.12 ± 0.16	8664.1 ± 0.4	11223.5 ± 0.4
$Q_{\beta x}$ (keV) ^a	280.7 ± 0.3	55.1 ± 0.5	2845.2 ± 0.2	285.7 ± 0.2

^aMass values from ref. [8]

2.3. Experimental considerations

Direct detection of these βp decays is challenging since one has to look for particles of low energy, with a low branching ratio, and where the decay branch has to be identified e.g. through particle identification (PID) techniques. As an alternative one may try to detect the presence of the daughter nucleus or, more ambitiously, its growing-in. In the cases in question here the final nucleus is stable or longlived so one cannot make use of its decay, but must resort to other methods. One possibility is accelerator mass spectroscopy (AMS) as explained in the next section.

A low branching ratio by itself does not prohibit direct detection. As an example, branching ratios well below 10^{-10} have been detected for cluster radioactivity [20]. The challenge is rather to identify the decay branch uniquely. For proton kinetic energies below 1 MeV one could employ gas telescopes and use the energy loss ΔE versus full energy E to identify the particle. However, the energy loss for a proton peaks just below 100 keV energy so the ΔE - E curves for protons, deuterons and tritons will cross in this region, making separation e.g. between protons and tritons (relevant for ^{11}Be) impossible. Identification via detection of E and time-of-flight is an alternative, but will typically have much less efficiency. Separating protons from the background of energy loss signals from beta particles could also be a problem.

If the proton can be recorded in coincidence with the recoiling nucleus this may be used to discriminate against other channels. This “ratio cut” method is useful to separate true events from response tails of events at higher energy, as done in the $\beta\alpha$ decay of ^{16}N [21] and needed here for the case of ^8B . It can also be used to single out one decay channel among many others, as done for the ^{11}Li beta-decay to $t+^8\text{Li}$ [22] and needed here for ^{11}Be . The main challenge with this method is to obtain efficient detection of the recoil with sufficient accuracy in energy, in the examples given the energy was higher than for our βp decays.

3. The ^{11}Be experiment

Four beta-delayed particle branches are energetically open for ^{11}Be , their Q-values are listed in table 1. We may neglect the βn branch since it would proceed to the ^{10}B 3^+ ground state and require a d-wave neutron with very low energy. The βt branch leads to ^8Be and would therefore give a three-body final state, this could also be a quite interesting decay mode. The main background for the βp branch will be $\beta\alpha$ whose branching ratio was measured to be $3.1 \pm 0.4\%$ [23] (a recent determination gave $3.47 \pm 0.12\%$ [24]).

3.1. The set-up and source production

Due to the challenges involved in direct detection of the βp decays we decided to explore the possibility of indirect detection. The βp -daughter nucleus, ^{10}Be , is radioactive with a half-life of $1.39 \cdot 10^6$ years and is only present on earth in minute quantities due to production by cosmic rays. It is used as a tracer in earth sciences and procedures have been developed for detecting very small samples of ^{10}Be via accelerator mass spectroscopy (AMS), see e.g. [25, 26]. Stated briefly, our experiment then consists in collecting a large number of ^{11}Be atoms, measure their number by detecting γ -radiation from the ^{11}Be decay and later measure the number of produced ^{10}Be atoms via AMS.

The ^{11}Be source was collected in September 2001 at the ISOLDE facility at CERN. The ^{11}Be atoms were produced by proton bombardment in a Ta target, ionized by laser ionization [27], accelerated and transported to the measuring station where the ion beam passed two sets of collimators before being implanted into a Be foil (Goodfellow, LS226536 L C, thickness 0.01mm, purity 99.8+%). The average intensity of the collected beam was $3.6 \cdot 10^6$ ions/s, the collection took place for close to 40 hours. The distance from the first collimator to the collection point was 177 mm. The transmission was optimized with a stable ^{23}Na beam and a radioactive ^{27}Mg beam, the fraction of the activity that deposited on the collimator was at most 12%.

3.2. Source strength

Most of the decays of ^{11}Be proceed through states in ^{11}B that decay by gamma emission, the most prominent γ -ray being the 2124.47 keV line with a total branching ratio, including feeding from higher levels, of $b_\gamma = 0.355 \pm 0.018$ [23]. The gamma detection was done with a Ge-detector that was placed about 40 cm from the collection point in the opposite direction of the collimator. It was further shielded by 3 mm Pb to reduce the total count rate. Still, the multi channel analyzer used for data taking had a deadtime of $14 \pm 1\%$ determined from the ratio of live time and real time of the data taking system.

The Ge detector was energy and efficiency calibrated *in situ* with absolutely calibrated sources of ^{60}Co , ^{137}Cs and ^{228}Th that bracket the energies from 239 keV to 2615 keV. The total gamma spectrum from ^{11}Be is shown in figure 2. The spectrum is dominated by gamma lines from the decay of ^{11}Be with a small background mainly from ^{40}K and the ^{222}Rn decay chain. The 2124 keV line is clearly separated from background and gives, after correction for detector efficiency and deadtime, a deduced amount of ^{11}Be atoms collected of $(5.2 \pm 0.3) \cdot 10^{11}$. As a cross-check of this number we shall look at two other γ -lines recorded from the ^{11}Be decay. First the 2895 keV line that again is nicely separated in our spectra; we deduce an intensity ratio with respect to the 2124 keV line of $0.241 \pm 0.011\%$ in agreement with the literature value of $0.227 \pm 0.008\%$ [23]. Secondly, we consider the 478 keV line that follows $\beta\alpha$ decays of ^{11}Be to the first excited state in ^7Li . The line is therefore recoil broadened and care must be taken when extracting its intensity since it furthermore is situated on top of a large background. Our deduced intensity relative to the 2124 keV transition is $0.75 \pm 0.06\%$.

The literature value for this last ratio can be derived from the decay scheme in [28] to be 1.13% (it was not observed directly since gamma detection was done with a NaI detector). However, as we shall argue now, this value is most likely wrong.

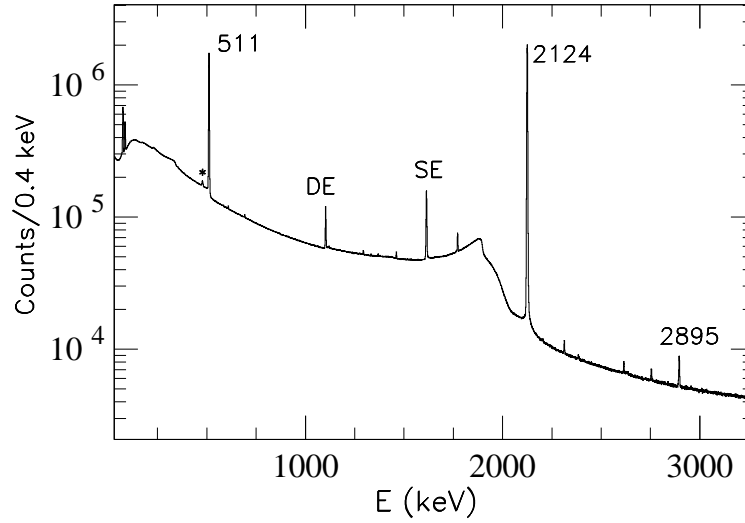


Figure 2. Gamma energy spectra recorded from the decay of ^{11}Be , the number of counts per 0.4 keV is shown versus gamma-ray energy. The star marks the 478 keV line.

Alternative determinations of this ratio measured with Ge detectors can be extracted from experiments on the decay of ^{11}Li in which ^{11}Be is fed. From two such recent experiments accurate results can be obtained (although not published previously): an experiment we did at ISOLDE [29] gave $0.67 \pm 0.11\%$ and an experiment at TRIUMF [30, 31] gave $0.69 \pm 0.07\%$. An unpublished recent $\beta\alpha$ experiment [24] has revised the branching ratio of alpha particles to the 478 keV excited state in ^7Li to be $8.0 \pm 0.4\%$ of all alpha decays, a result based on a detailed analysis of the alpha spectrum but in disagreement with the literature value of $12.6 \pm 1.2\%$ [28]. Using the new value one derives a 478/2125 ratio of $0.78 \pm 0.06\%$. Since the three new determinations all are consistent with our value for the ratio, we conclude that our spectra are internally consistent which adds confidence to our derived source intensity.

3.3. Source purity

The collection foil must of course be free of previous ^{10}Be activity, but we also need to worry about contamination coming along with the ^{11}Be beam. The most worrisome contaminant is ^{11}Li that can be ionized by surface ionization in the hot cavity where laser ionization of Be takes place. The primary production yield is lower by a factor at least 2000, but the main decay branch of ^{11}Li is beta-delayed one-neutron emission that leads to ^{10}Be and suppression of ^{11}Li is therefore needed.

The mass difference between ^{11}Be and ^{11}Li , $\Delta M = Q(^{11}\text{Li}) = 20.551 \text{ MeV}$ [8], is sufficiently big that the resolving power of ISOLDE's high resolution separator HRS, which is up to $M/\Delta M = 5000$, can easily separate the two nuclei that have $M/\Delta M = 500$. A tail of ^{11}Li activity may nevertheless be present at the ^{11}Be mass position, but we have estimated its magnitude by looking for the corresponding tails of the nuclei ^9Li and ^8Li a factor $M(^{11}\text{Be})/M(^{11}\text{Li})$ below their nominal setting. In both cases background prevented a direct identification — there are no γ -rays in

Table 2. Results of AMS measurements.

Subfoil	Mass (mg)	$R=R_{\text{foil}}/R_{\text{SRM}}$	^{10}Be (10^6 atoms/mg)
A (blank)	3.04	0.00149(12)	2.67(22)
B (background)	3.65	0.00152(11)	2.73(20)
C (catcher)	4.22	0.00169(13)	3.03(23)

either decay, so only the (non-unique) β -detection is possible — but a lower limit of the suppression factor of 10^3 was extracted in both cases. A second source was collected with the separator deliberately set off-mass by two thirds of the ^{11}Li - ^{11}Be mass difference (below the ^{11}Be position). The intensity of the ^{11}Be gamma lines was here reduced by a factor 500, consistent with the results at the lower masses.

A further reduction can be obtained by blocking collection for the first 150 ms after the radioactivities are produced by the proton pulse. Most ^{11}Li , of half-life 8.5 ms, will have decayed by then. However, at the end of our collection it was discovered that the onset of the blocking by mistake was delayed by a few ms allowing up to 15% of the ^{11}Li to leak through. Thus up to $2 \cdot 10^4$ ^{10}Be could have contaminated the sample through decay of collected ^{11}Li .

A second possible contaminant could be the BeH molecule $^1\text{H}^{10}\text{Be}$ that would be almost on top of the ^{11}Be mass since $M/\Delta M = 36600$ for this case. It is quite unlikely that this molecule will be formed and ionized in sufficient quantities to be a problem, but the possibility should be kept in mind in future experiments. As will be seen we do not have indications for any of these contaminants in the present sample.

3.4. AMS measurement

The ^{10}Be accelerator mass spectrometry (AMS) measurements were performed at the Tandem Laboratory, Uppsala University, in Sweden [32]. A dedicated setup based on a NEC 5 MV tandem pelletron accelerator devoted to high precision and low background detection of ^{10}Be was employed. The measurements were carried out according to the principle presented by Middleton and Klein [33, 34] where ion currents were normalized by ^{17}O from the $^9\text{Be}^{17}\text{O}$ molecule. The absolute transmission in the AMS-system was determined with the NIST SRM 4325 standard ($^{10}\text{Be}/^9\text{Be} = 3.06 \cdot 10^{-11}$ [33]; NIST certificates the ratio to be $R_{\text{SRM}} = 2.68 \cdot 10^{-11}$).

The Be-foil used in the investigation was divided into three 10×10 mm² samples where one subfoil A was just chemically prepared and used as a blank value representative for the whole AMS procedure. Subfoil B and C were both mounted in two aluminium frames with a circular aperture (diameter 8 mm). Both were installed in the ISOLDE facility. There was no implantation in subfoil B while subfoil C was used as the catcher for ^{11}Be .

All three subfoils were chemically prepared by dissolution in HCl followed by precipitation to $\text{Be}(\text{OH})_2$ by adding NH_3 which in turn was converted to BeO. Finally the BeO was mixed with Nb as a binder before the AMS-analysis in the accelerator.

A summary of the results is given in table 2. No significant difference is observed for the blank and background foils which indicates no additional ^{10}Be contamination in the handling in ISOLDE and during transportation. It is, however, noteworthy to compare the background values for the foil used with what is obtained from our

normal Be carrier which for 1 mg sample gives a $R = 0.0005(1)$ corresponding to a factor two lower ^{10}Be content.

If we use subfoil B as a background to subfoil C the ^{10}Be signal can be estimated to be $(1.28 \pm 1.29) \cdot 10^6$ atoms. With a total number of ^{11}Be nuclei in the sample of $(5.2 \pm 0.3) \cdot 10^{11}$ this leads to a deduced branching ratio of $(2.5 \pm 2.5) \cdot 10^{-6}$ where the uncertainty is on the one sigma level. There is therefore no positive evidence for the ^{11}Be βp decay, only an upper limit of the order of the most optimistic theoretical branching ratios.

4. The ^8B experiment

The ^8B experiment was carried out at the IGISOL (Ion Guide Isotope Separator On-Line) separator at the Accelerator Laboratory of University of Jyväskylä. The main aim of this experiment was to determine precisely the neutrino spectrum from the decay of ^8B through analysis of the beta-delayed alpha spectrum. The result of this part of the experiment along with a detailed description of the experimental procedures is described in [36, 37]; the set-up consisted of four DSSSD detectors each backed by a thick Si detector in close geometry around the collection point. As a byproduct the high statistics of the experiment allowed to identify for the first time an electron capture branch in the decay of ^8B , namely to the 2^+ 16.922 MeV state. We are here concerned with the possible electron capture branch to the even higher-lying 17.640 MeV state.

Since the ^8B experiment recorded a total of 16 million decays, the expected number of proton detections is 0.36 and we can only report an upper limit. The 17.640 keV state will decay by emitting a 337 keV proton and a 48 keV recoiling ^7Li ion that could not be detected. The main background from the decay will be α - α coincidences at low energy or positrons that happen to deposit around 340 keV in the detector. The latter background can be suppressed by requiring anti-coincidence with the backing detectors. The former background needs to be addressed indirectly since the set-up did not include particle identification. One can suppress the α particles by doing anti-coincidence with the opposite DSSSD, but to do this efficiently one needs to restrict the solid angle and only consider events close to the center of each DSSSD since beta-recoil can cause the α coincidences to deviate from a linear geometry. This reduces the effective solid angle by a factor about 9. A small background nevertheless remains, see figure 3, and the 95% confidence level upper limit of the number of counts in a 337 keV peak turns out to be 18. As seen in the figure there are indications for a peak at 349 keV; however, the uncertainty on the energy scale is only 7 keV since there were accurately known calibration lines from the decay of ^{23}Al close by [38]. The 95% confidence level upper limit on the number of counts in the 349 keV peak is 45. Combining all factors gives an upper limit of $2.6 \cdot 10^{-5}$ on the βp branching ratio at 95% confidence level. To reach the range of predicted intensity the experiment needs to improve by a factor 1000. One may gain a factor of ten by including particle identification, which will reduce the background in the interesting energy range. Another factor of ten may be obtainable by increasing the effective solid angle, but one still would need a factor of ten higher overall production of ^8B ions.

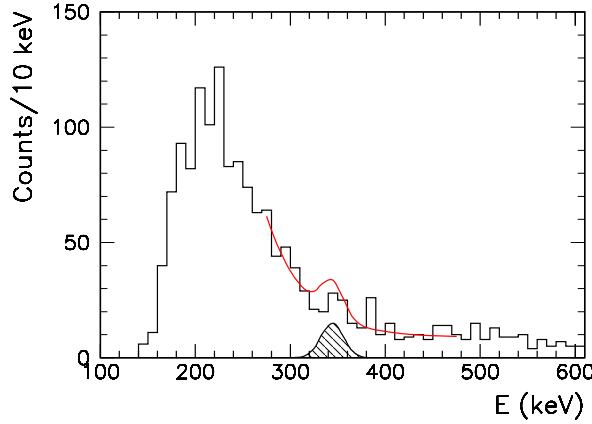


Figure 3. The low-energy spectrum from the decay of ^8B after background suppression. The red curve shows the two sigma upper limit from of a fit where the peak position was allowed to vary within uncertainties.

5. Outlook

The theoretical estimates in section 2 showed that beta-delayed proton emission in the decays of ^{11}Be and ^8B is likely to take place with a branching ratio that can be expected to be a few times 10^{-8} . The energies of the emitted proton and the recoiling nucleus will be small. These two factors make detection of the processes challenging.

We have carried out first experiments to look for these decay branches and have obtained upper limits on the branching ratios. These do not yet reach the level of the theoretical predictions, improvements are needed by factors of at least 10^2 and 10^3 for the two cases. The continuing improvements of radioactive beam facilities may give increases in the yields that will allow experiments to reach the needed level of sensitivity, but other possible improvements should also be considered. As explained above for ^8B changes to a more dedicated set-up should be considered. For the case of ^{11}Be the AMS measurement can be considerably improved if the amount of stable Be in the sample is reduced. This can be achieved by using a different catcher foil (e.g. Cu, Au or Nb) and after adding a small amount of Be carrier (< 0.1 mg with low ^{10}Be content) do a refined chemical separation [35]. An enhanced sensitivity of two orders of magnitude can be expected from such improved sample handling.

Once the decay modes have been established and the branching ratio securely determined, the next important step will be to determine the energy distribution of the emitted protons. This will give a more sensitive test of the theoretical calculations and may in particular show whether our hypothesis of a direct relation between the βp decay mode and the halo structure in these two nuclei is correct.

Acknowledgments

We would like to thank I. Mukha and L. Grigorenko for discussions and F. Sarazin for communicating non-published results on the ^{11}Li decay. This work was partly

financed by the Spanish Research funding agency under project CICYT FPA2007-62170 and FPA2009-07387 and by MINECO through projects FPA2010-17142 and CPAN CSD-2007-00042.

References

- [1] Nilsson T, Nyman G and Riisager K 2000 *Hyperfine Int.* **129** 67
- [2] Jonson B and Riisager K 2001 *Nucl. Phys.* **A693** 77
- [3] Pfützner M, Karny M, Grigorenko LV and Riisager K 2012 *Rev. Mod. Phys.* **84** 567
- [4] Blank B and Borge MJG 2008 *Prog. Part. Nucl. Phys.* **60** 403
- [5] Riisager K, Fedorov DV and Jensen AS 2000 *Europhys. Lett.* **49** 547
- [6] Jensen AS, Riisager K, Fedorov DV and Garrido E 2004 *Rev. Mod. Phys.* **76** 215
- [7] Jonson B 2004 *Phys. Rep.* **389** 1
- [8] Georges Audi and Wang Meng, private communication, April 2011
- [9] Angélique JC et al. 1998 Experiment proposal CERN/ISC 98-6 ISC/P99
- [10] Ajzenberg-Selove F 1990 *Nucl. Phys.* **A506** 1
- [11] Yamaguchi H et al. 2011 *Phys. Rev.* **C83** 034306
- [12] Barker FC 1989 *Aust. J. Phys.* **42** 25
- [13] Borge MJG et al. 1993 *Nucl. Phys.* **A560** 664
- [14] Barker FC 1994 *Phys. Lett.* **B322** 17
- [15] Riisager K et al. 1990 *Phys. Lett.* **B235** 30
- [16] Baye D and Tursonov EM 2011 *Phys. Lett.* **B696** 464
- [17] Tilley DR, Kelley JH, Godwin JL, Millener DJ, Purcell JE, Sheu CG and Weller HR 2004 *Nucl. Phys.* **A745** 155
- [18] Bambynek W et al. 1977 *Rev. Mod. Phys.* **49** 77
- [19] Grigorenko LV, Shul'gina NB and Zhukov MV 2000 *Nucl. Phys.* **A665** 105
- [20] Price PB 1989 *Annu. Rev. Nucl. Part. Sci.* **39** 19
- [21] Azuma RE et al. 1994 *Phys. Rev.* **C50** 1194
- [22] Madurga M et al. 2009 *Eur. Phys. J.* **A42** 415
- [23] Millener DJ, Alburger DE, Warburton EK and Wilkinson DH 1982 *Phys. Rev.* **C26** 1167
- [24] Büscher J 2010 PhD thesis, Katholieke universitet Leuven, unpublished
- [25] Elmore E and Phillips FM 1987 *Science* **236** 543
- [26] Müller AM et al. 2008 *Nucl. Instr. Meth.* **B266** 2207
- [27] Fedosseev VN et al. 2003 *Nucl. Instr. Meth.* **B204** 353
- [28] Alburger DE, Millener DJ and Wilkinson DH 1981 *Phys. Rev.* **C23** 473
- [29] Fynbo HOU et al. 2004 *Nucl. Phys.* **A736** 39
- [30] Mattoon CM et al. 2009 *Phys. Rev.* **C80** 034318
- [31] Sarazin F 2009 private communication
- [32] Berggren AM, Beer J, Possnert G et al. 2009 *Geophysical Research Letters* **36** L11801
- [33] Middleton R and Klein J 1986 in *Workshop on Techniques in Accelerator Mass Spectrometry* ed R Hedges and E Hall, UK p 76
- [34] Middleton R, Brown L, Dezfouly-Arjomandy B and Klein J 1993 *Nucl. Instr. Methods* **B82** 399
- [35] Berggren AM, Aldahan A, Possnert G et al. 2009 *Geochimica et Cosmochimica Acta* **73** A112
- [36] Kirsebom OS 2010 PhD thesis, Aarhus University, unpublished
- [37] Kirsebom OS et al. 2011 *Phys. Rev.* **C83** 065802
- [38] Kirsebom OS et al. 2011 *Eur. Phys. J.* **A47** 130